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U. S. NAVY DEVELOPMENT OF AN ON-BOARD OXYGEN GENERATION (OBOG) SYSTEM

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6 DECEMBER 1978

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The Naval Air Development Center has been conducting a development program to explore the On-Board Oxygen Generation (OBOG) concept for application aboard tactical naval aircraft. The objective of the program is to eliminate hazardous and logistically burdensome LOX (liquid oxygen) installations on ships, as well as forward basing areas, by generation of oxygen on board the aircraft. over

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The technical approach involved the complete comparative development of open loops oxygen generators for the separation of oxygen from engine bleed air. Three conceptual approaches were taken: (1) "Fluomine" reversible sorption of pure (100%) oxygen, (2) Electrochemical separation of pure (100%) oxygen, (3) Molecular sieve adsorption/desorption of (95%) oxygen breathing gas.

The purpose of this paper is to report on progress to date in the program which includes: (1) Major reduction in values of weight and resource requirements to acceptable levels, (2) Development of hardware prototypes of the proposed systems suitable for flight test, (3) Aircraft/OBOG systems integration studies, (4) Laboratory T&E of the prototype systems, (5) Physiological assessment (man rating) of the prototype systems, (6) Flight testing to date.

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INTRODUCTION

Operational and combat missions are routinely conducted by military aircraft at altitudes where the partial pressure of oxygen in the atmosphere is insufficient to meet physiological requirements of aircrew members. The required source of breathing oxygen is presently supplied by either gaseous or liquid oxygen (LOX) systems. These systems require generation of oxygen aboard the carrier and servicing of the aircraft prior to each flight, which imposes a major logistic burden on the ship or shore base. Other specific LOX problems are:

1. 2300 ft^2 of deck space and 60,000 lb of LOX support equipment are required on a typical carrier.

2. Storage and transfer systems are subject to frequent contamination of entire supplies which required COD delivery to the CV or remote base.

3. High evaporation (40 percent) of LOX due to inefficient transfer systems.

4. Quantities of LOX are susceptible to combat damage and are a safety hazard both to aircraft/ships and personnel.

5. Carrier and shore-base fires can be directly attributed to spillage of LOX, causing loss of lives and equipment.

The Navy decision to deploy aircraft aboard nonaviation ships and forward bases further complicates the problem since these ships cannot provide the necessary space required for the generation, transfer, and storage of LOX. It is also unacceptable to make these ships dependent upon carriers and other ships for LOX and to limit their operational employment.

Introduction of on-board oxygen generation (OBOG) systems as an alternative to the present method of oxygen supply both reduces present burdens and makes the VSTOL/nonaviation ship concept practical. The goals of the development program are to reduce support personnel requirements by 70 percent, eliminate 30 tons/2300 ft^2 of equipment from aircraft carriers, increase reliability and maintainability by modular replacement, achieve 1000-hr maintenance interval, 15-hr service interval, 5000-hr mean time between failure (MTBF) and have an estimated annual cost saving of $45M.

SYSTEM DEVELOPMENT

METHODS AND INVESTIGATION

The fluomine sorbent process and the electrochemical concentrator process were selected for prototype development as a result of a joint Navy/Air Force program evaluation of various proposed oxygen generation methods. A water electrolysis method and a barium oxide/dioxide reversible process were also studied but disqualified for further consideration due to elevated levels of complexity and requirements of logistics support. Parallel to the above joint Navy/Air Force effort, the concept of molecular sieve oxygen separation was also explored by the Navy. Although only capable of providing a maximum of

95-percent oxygen, the simplicity of the molecular sieve concept and its relatively minimal aircraft resource requirements make it a viable candidate.

All OBOG systems used the F-14 airframe as a design guide for interface and resource integration, and had an output requirement of 4.6 lb/hr (26.2 lpm) oxygen to meet the specification of a two-man open-loop breathing schedule.

FLUOMINE SYSTEMS (100 PERCENT OXYGEN)

The design, development, and fabrication of the fluomine system has been well documented[1.,2.,3.,4.] Basically the system employs two beds containing approximately 22 lb of fluomine, which are cyclically operated to produce a steady flow of oxygen from engine bleed air. The engine bleed air at 50 psi is regulated to 25 psi and directed to the sorbent beds containing the cobalt chelate, commercially known as fluomine, where oxygen is absorbed with the remaining gas vented to ambient. At the end of a 3½-min cycle, bed pressure is decreased to 7 psi and the bed temperature raised to 220-225°F to release the oxygen. The desorbed oxygen then flows to a three-stage positive displacement compressor where the pressure is raised to be compatible with existing oxygen equipment (70 psi nominal) and storage containers (1800 psi nominal) (figure 1).

The prototype system, as delivered, has a volume of 3 ft^3 (25.6 in. W, 13.5 in. H, 15.0 in. D), and weighs 140 lb. The system requires aircraft resources of: 50 lb/hr (-35° to 75°F, 25 to 80 psi) air, 800 to 1200 lb/hr (75° to 120°F, 20 psi) Coolanol 25 to remove a heat load of 14,000 to 18,000 btu/hr, 550 lb/hr heating air at 445°F, and 0.1 kw 28 vdc, 1.1 kw 114 vdc 400 Hz electrical power.

ELECTROCHEMICAL SYSTEM (100 PERCENT OXYGEN)

The design, development, and fabrication of the electrochemical system has also been well documented[1.,2.,3.,4.] The system passes engine bleed air through a heat exchanger jacket surrounding a water tank and into the air cavities of 120 electrochemical cells in a concentrator stack. As current flows through the cells, the water molecules are electrolyzed into oxygen and two protons. The protons carry the current through the solid polymer electrolyte and combine with oxygen in the bleed air to form water. Controlling the flow of bleed air through the cells regulates the operating temperature of the cells to 180°F. As oxygen is generated, it is fed through a oxygen chiller to an oxygen/water separator where water is extracted and returned to this water tank. Water is required to keep the cells at 100 percent humidity to maintain efficient cell performance, but there is no production or consumption of water. After the water is separated, the oxygen passes through a check valve and into an accumulator. Maximum design oxygen generation pressure is 380 psi with the accumulator sized for an emergency reserve, and no compressor necessary (figure 2).

The prototype system, as delivered, has a volume of 2.8 ft^3 (25 in. W, 13 in. H, 15 In. D) and weighs 85 lb.

The system requires aircraft resources of: 115 lb/hr (500° to 300°F, 25 to 80 psi) air, 1330 lb/hr (75°F, 5 psi) Coolanol 25 to remove a heat load of 28,200 btu/hr, and 6.4 kw 114 vac 400 Hz electrical power.

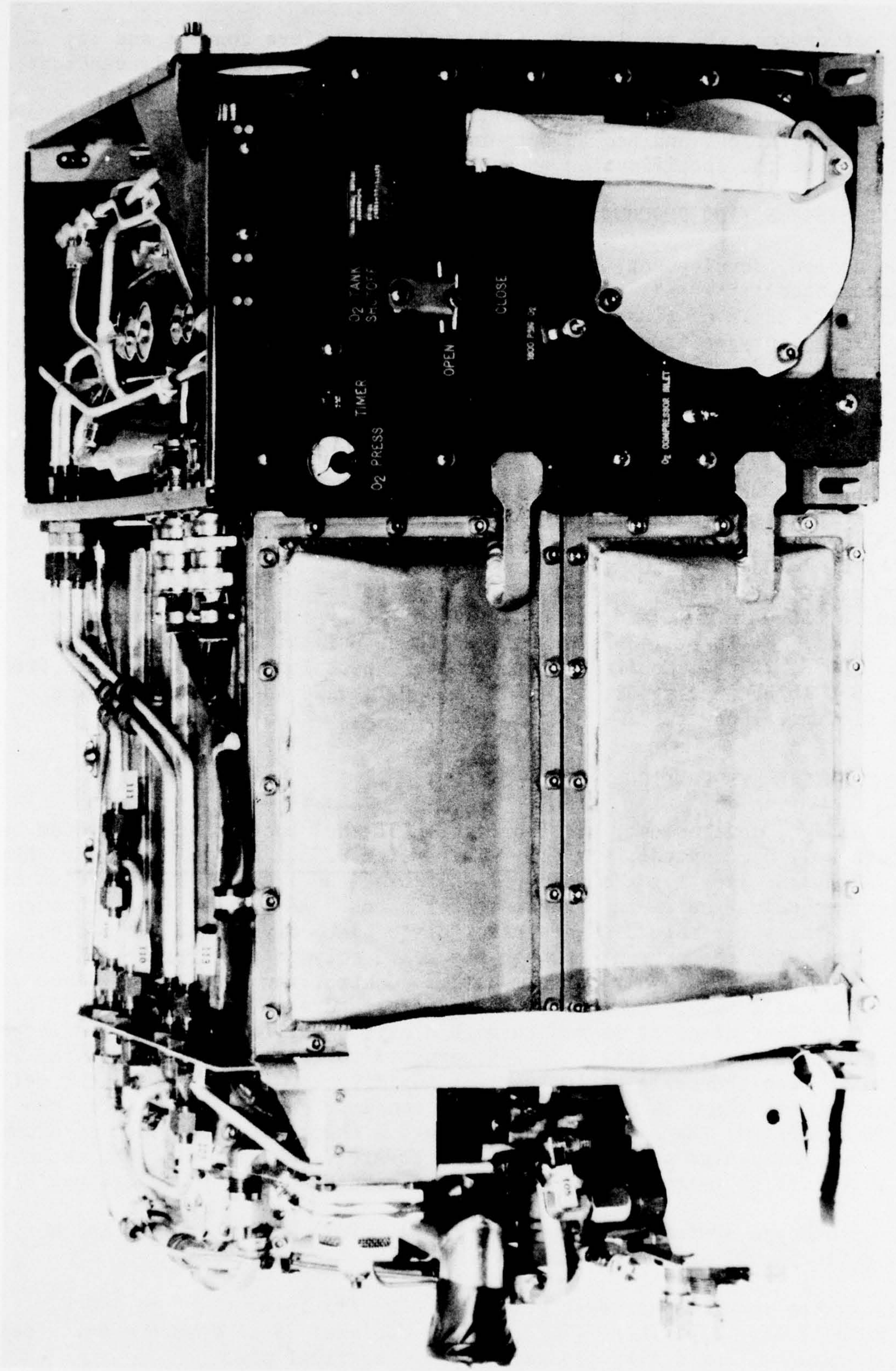

FIGURE 1 - Prototype Fluomine OBOG System.

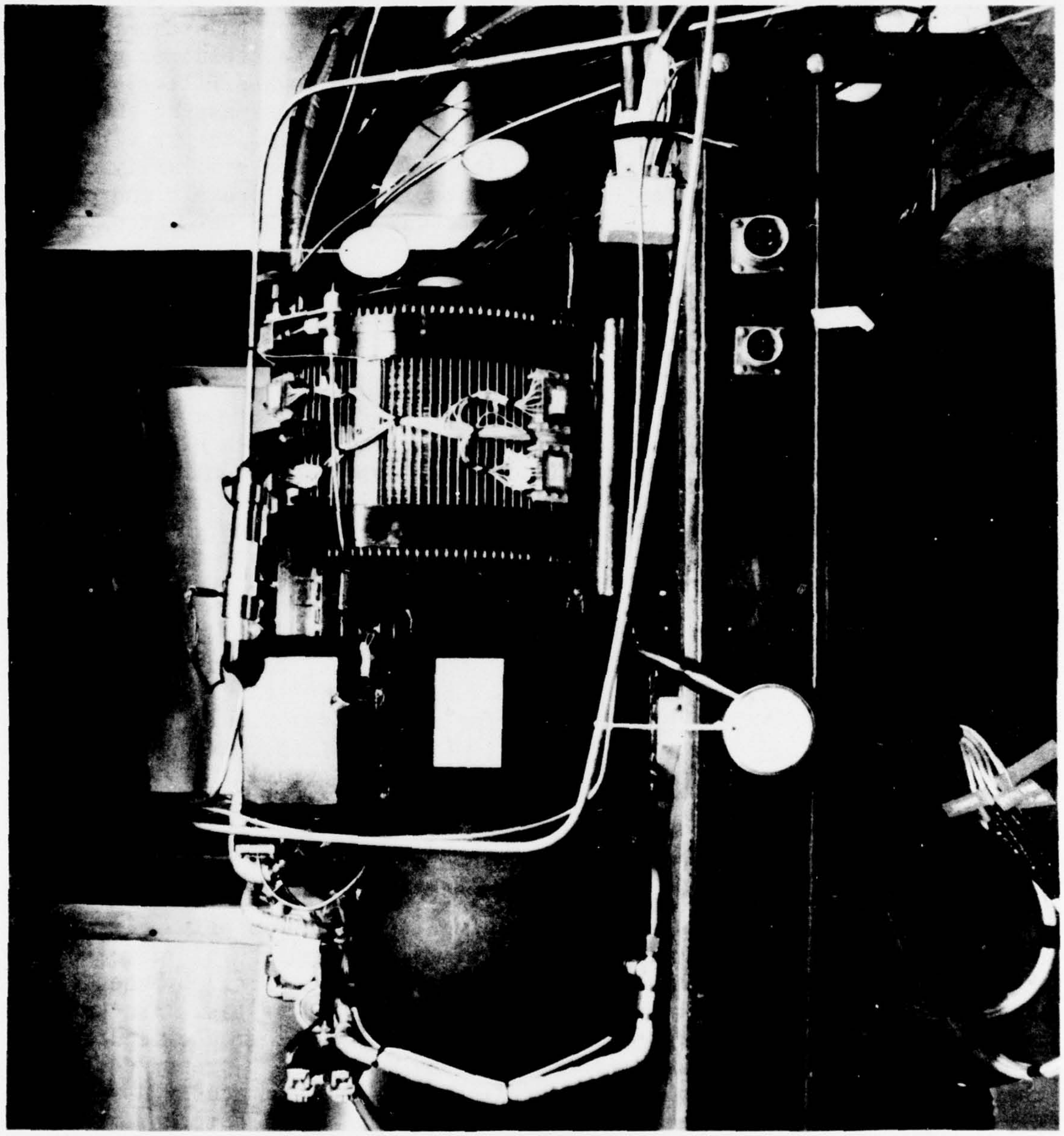

FIGURE 2 - Prototype Electrochemical OBOG System.

MOLECULAR SIEVE SYSTEM (95 PERCENT OXYGEN)

The design, development, and fabrication of the molecular sieve system is also well documented[1.,2.,3.,5.] The system utilized two beds containing 11 lb of the crystalline aluminosilicate compounds, also known as zeolites, which are alternately operated to produce a steady flow of oxygen. Since the adsorption process retains molecules by Van der Walls forces, rather than chemical bonding, the process can be reversed by a pressure swing cycle and requires no heating or cooling. Bleed air is admitted to a sieve bed through a filter, regulator, and rotating inlet valve with the oxygen-enriched product passing into an accumulator. A portion of the oxygen-enriched air is used to purge the desorbing bed by means of a purge control orifices. Due to the similarity of the oxygen and argon molecules both are separated from the bleed air and concentrated in the oxygen-enriched product with a maximum of 95 percent oxygen and 5 percent argon (figure 3).

The prototype system, as delivered, has a volume of 1.3 ft^3 (12 in. W, 13 in. H, 15 in. D) and weighs 55 lb. The system requires aircraft resources of air averaging 55 lb/hr (40° - 100°F, 25 to 120 psi) air at maximum pressure and flow, and 5.6 w 28 dc power.

The molecular sieve portion of the OBOG program has been expanded by the Navy and the effort has progressed to the development of a unit to meet the requirements of the AV-8A "Harrier" (figure 4). The Harrier is the first in the VSTOL generation of aircraft currently operational. The envelope requirements are smaller for the AV-8A than the F-14 and the output requirement of 2.3 lb/hr (13.1 lpm) of oxygen is also reduced. Prototype systems, already delivered, for the AV-8A have a volume of 0.88 ft^3 (12.9 in. W, 10.1 in. H, 11.6 in. D) and weigh 35 lb. The volume compares favorably with both the 10-liter and 5-liter LOX converters, 1.6 and 1.06 ft^3, respectively. Resources identified as available from the AV-8A, of 55 lb/hr (0° to 250°F, 8 to 250 psi) air and 600 w 28 vdc power are provided for system operation. The increased power requirement is to provide thermal control (heating) during low-temperature operation. If heating is not required, the system operates on 50 w maximum.

PROGRAM PROGRESS

The initial phases of the OBOG development effort were primarily concerned with the fluomine and electrochemical concepts. The molecular sieve concept was given secondary consideration due to restrictions imposed by the low oxygen content (75 percent max.) of the evolved breathing gas. As the development effort progressed and the proposed fluomine and electrochemical concepts evolved into hardware configurations, problems arose which presented formidable complications. Corrective actions ranging from subsystem redesign to disassembly and rework were required on the prototype systems. The technical problems also resulted in varying system operational parameters, performance, and penalty assessments. Concurrent with the development problems arising in the two primary systems, the technology of the molecular sieve concept evolved to where 95 percent oxygen production had been demonstrated by laboratory systems.

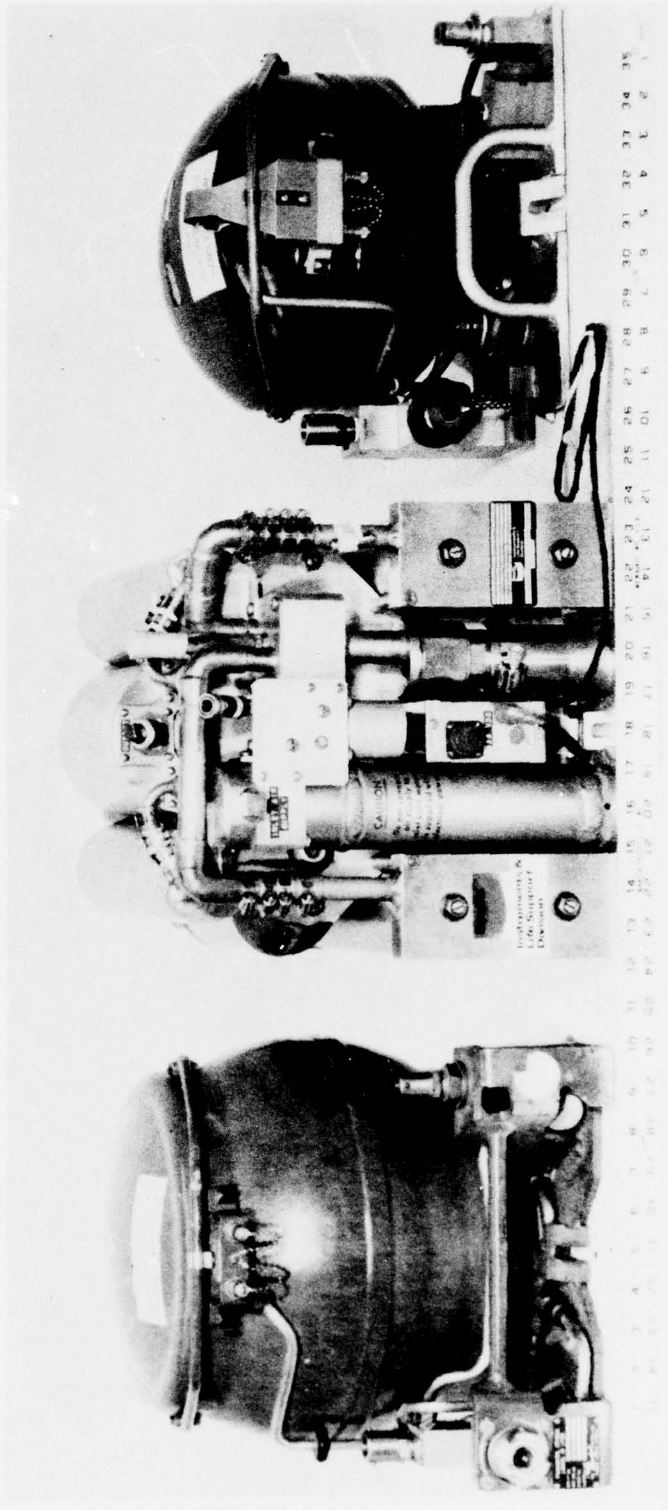

FIGURE 3 - Prototype Molecular Sieve OBOG System.

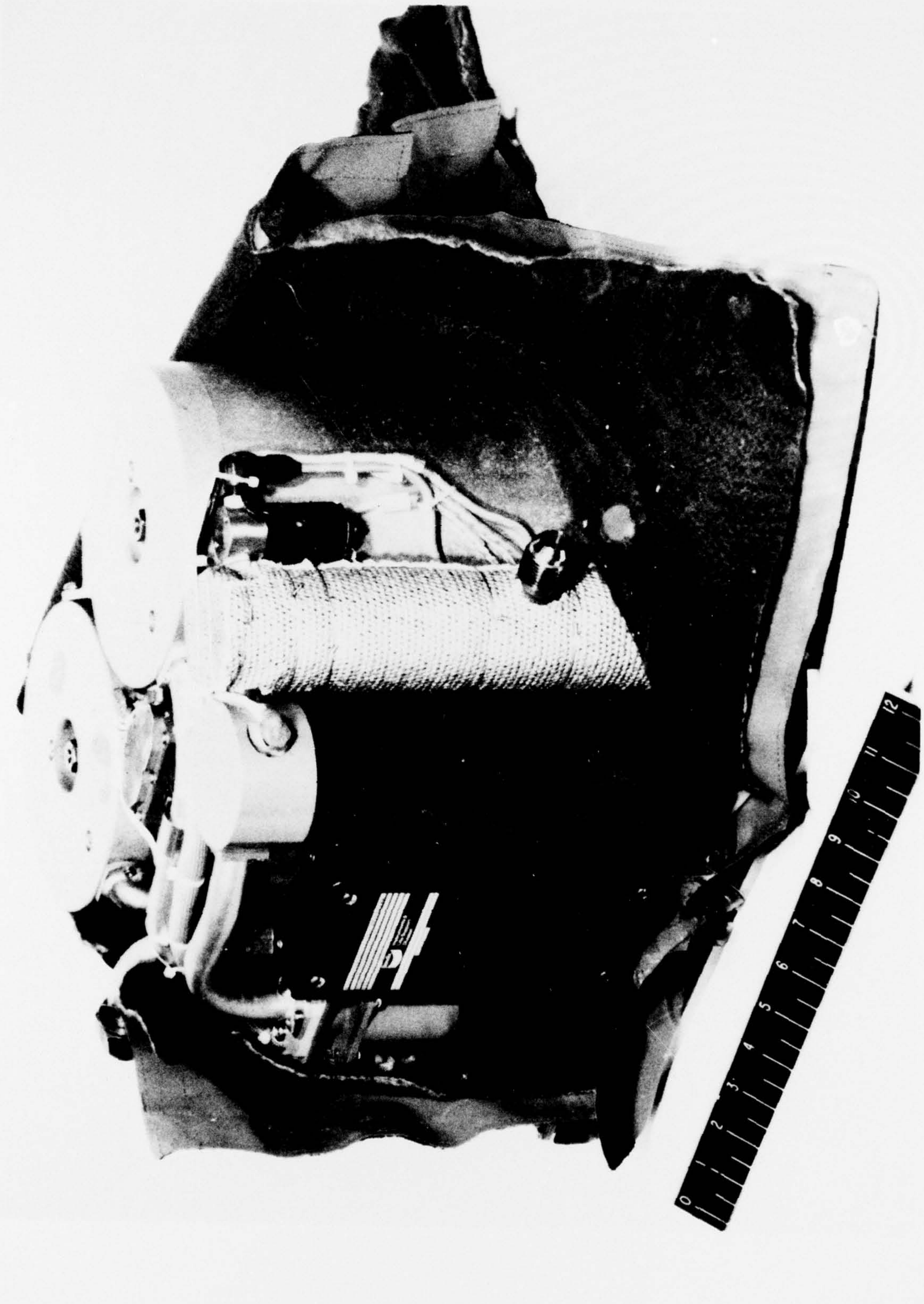

FIGURE 4 - Prototype Molecular Sieve OBOG System for the AV-8A Harrier.

This advance, coupled with the rescinding of the requirement for 100 percent oxygen for breathing gas by naval aviators[6], drastically altered the consideration given the molecular sieve concept.

AIRCRAFT/OBOG SYSTEM INTEGRATION STUDIES

The objective of the study, as documented[4], was to enhance the integration of the proposed systems, as modified during hardware development, into operational aircraft. The designated design guide for this purpose was the F-14 with the AV-8A included, since it is a VSTOL aircraft with critical weight and performance requirements.

It was determined that all three systems could be accommodated into the F-14 aircraft in the space provided by the two existing 10-liter LOX converters. Additional space would be required for supplementary oxygen storage requirements. It was also determined that hypothetical one-man fluomine and electrochemical systems could be installed in the AV-8A provided a modular design was utilized, since the total space available is not in one location.

The integration study also determined that although the fluomine and electrochemical systems provide 100 percent oxygen breathing gas, their resource requirements are not available in all candidate tactical aircraft, including the AV-8A, without major modification and associated performance penalties. The F-14, which represents current state-of-the-art technology and contains a relatively large and complex Environmental Control System (ECS), generates the resources required by the OBOG systems. These resources, however, are not always available in sufficient quantities, due to varying consumption rates of other equipment and weapon systems.

Although the molecular sieve is a viable contender, since it has minimal impact of airframe and resource requirements, it requires the modification of existing oxygen regulators. The molecular sieve system operates from engine bleed air at pressures below 10 psi without a compressor to boost the breathing gas to a range (70 psi nominal) compatible with existing regulators.

As stated above, the Navy OBOG effort has included development and fabrication of molecular sieve systems for the AV-8A. This development included a regulator compatible with the output pressure range of the unit and a cockpit-mounted oxygen percentage sensor. The unit will meet the requirements of a one-man open-loop breathing schedule with oxygen percentage exceeding that provided by the current diluter-demand regulators.

LABORATORY TEST & EVALUATION

The laboratory T&E program was relaxed from requirements of full qualification to flight worthiness due to the prototype nature of the systems being tested. This derating would minimize the risk of damage and ensure that the anticipated service life of the systems would be sufficient for laboratory T&E, man rating, and developmental flight testing. The objectives of the laboratory test program are to verify that the system will not be hazardous to aircraft

or personnel during flight test, to verify that design criteria has been attained, and to evaluate each system's performance characteristics in the proposed flight test environment. The test program included: performance measurements in the environment anticipated during flight test, temperature and altitude combinations, vibration, and acceleration.

The laboratory T&E of the electrochemical produced unsatisfactory results with the system performance below requirements. Trouble shooting and repair failed to raise the performance to an acceptable level and necessitated termination of the remainder of the test program for this system.

During the laboratory T&E of the fluomine system the unit produced up to 32 lpm (26.2 lpm required) of oxygen at 94-percent purity with acceptable levels of carbon dioxide and carbon monoxide. Heat loads up to 18,000 btu/hr were observed. During cold soak (-45°F) there was a failure (blown fuses, compressor freeze-up) of the system; however, it is anticipated that the system will not experience this condition during flight test. After rework of the unit, the oxygen purity increased to 99.6 percent, but oxygen production dropped to 19-22 lpm. The unit successfully completed vibration testing with no structural, functional, or performance degradation, and it was forwarded to the Pacific Missile Test Center to verify installation/integration in the modified EA-6B flight test aircraft. The system's sorbent beds were repacked and the system forwarded to Brooks AFB for physiological assessment (man rating).

The laboratory T&E of the molecular sieve system[7] was successfully completed. Critical parameters identified for close surveillance during flight test were: inlet air pressure, ambient temperature, outlet flow rate, and oxygen concentration. Structural integrity of the system was demonstrated during vibration and acceleration testing with no structural, functional, or performance degradation. The system was also forwarded to Pacific Missile Test Center to verify installation/integration into the test aircraft.

Laboratory T&E of the AV-8A molecular sieve system is currently underway and has been successful to date. Oxygen purity is well within the required values at the design points. Cold soak (-65°F) start up tests were successfully completed. Performance evaluation will continue and be followed by vibration and acceleration tests prior to flight test.

PHYSIOLOGICAL ASSESSMENT (MAN RATING)

The physiological assessment portion of the laboratory T&E program is required to verify human compatibility of the proposed system. This was determined while the prototype systems delivered breathing gas to human subjects under anticipated flight conditions. This portion of the program was conducted by the USAF School of Aviation Medicine at Brooks Air Force Base.

The physiological assessment of the molecular sieve system[8] preceded that of the fluomine system due to program milestones and events. The electrochemical system was not tested. The physiological assessment of the molecular sieve system indicated that it was qualified for flight test in the EA-6B. The unit provided sufficient oxygen for hypoxia protection to altitudes of 28,000

ft, and with compatible pressure demand regulation will provide oxygen pressure for protection up to 44,000 ft. The argon concentration in the product gas varied from 1.8 to 5.2 percent, depending upon conditions.

As a part of the molecular sieve physiological assessment, the effects of breathing a gas mixture containing argon were also investigated. Particular emphasis was placed on the effects of the gas during decompression. Although the documentation is not yet published[9], the results indicated there would be no adverse effect.

The fluomine system also successfully completed the physiological assessment portion of the laboratory T&E program, and it was forwarded to the Naval Air Development Center where it successfully completed acceleration testing.

FLIGHT TEST

The Pacific Missile Test Center (PACMISTESTCEN) was tasked to conduct the flight test phase of the developmental test and evaluation of the OBOG prototype units upon successful completion of the laboratory T&E program and man rating. An EA-6B was selected as the test bed aircraft because it has the necessary resources (cooling, bleed air, electrical) to simulate the F-14, and an aircraft was available that was not a full systems fleet asset. A modification kit to interface the different OBOG systems was designed and fabricated by Grumman Aircraft Corporation[10] and, together with the required instrumentation, installed by PACMISTESTCEN (figure 5). Actual flight testing has been conducted by the Naval Air Test Center (NAVAIRTESTCEN) Patuxent River, Maryland under the cognizance of the PACMISTESTCEN.

The flight test plan was developed to evaluate the OBOG systems under conditions simulating the intended operational environment. The systems would be monitored for oxygen purity, production, resource usage and effects on other aircraft systems, and for structural integrity. Four product samples will be obtained during each test and analyzed. Following the completion of each test, engineering and physiological data acquired on magnetic tape will be analyzed. The program will include ground and flight tests. Ground operations will include calibration tests and tests behind an operating jet aircraft to determine the effect of contaminated intake and bleed air on oxygen production and purity. Flight tests will include straight and level flights, inverted flight, climb and descent, aerobatic maneuvers, takeoff and landing, simulated carrier launch and recovery operations, tactical warfare mission simulation, percipitation encounters, in-flight refueling, and simulated emergency (engine, generator shut down) conditions (figures 6 and 7).

Flight testing commenced April 1978 at NAVAIRTESTCEN with the molecular sieve system after successful ground installation and test at PACMISTESTCEN. Low-pressure regulators, developed for the AV-8A system but also compatible with the system in the aircraft, are being utilized in the test program. To date, no problems have developed with the system, no trace contaminants found in the oxygen, and oxygen purity adequate when compared with the time in the

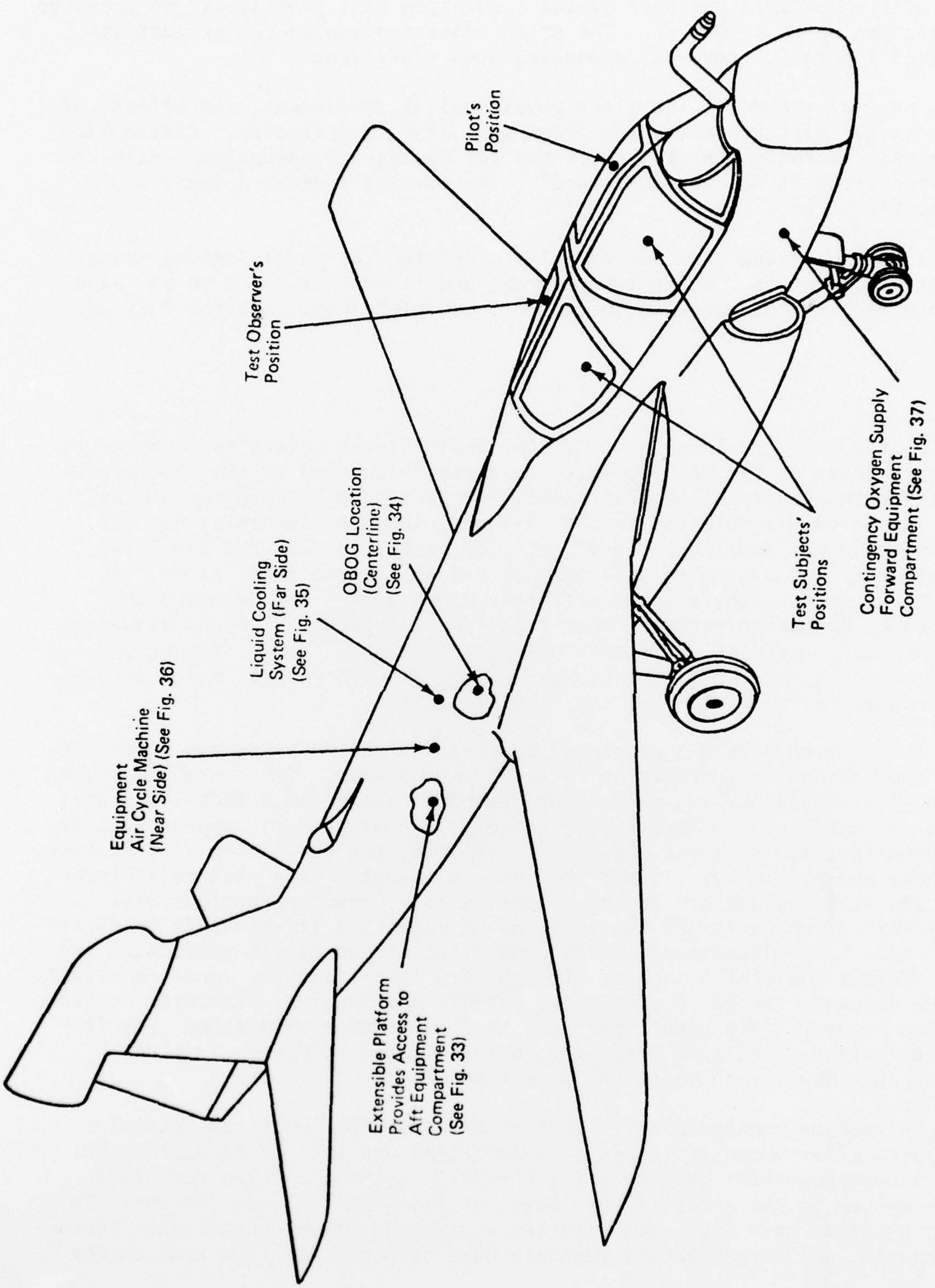

FIGURE 5 - EA-6B Overview.

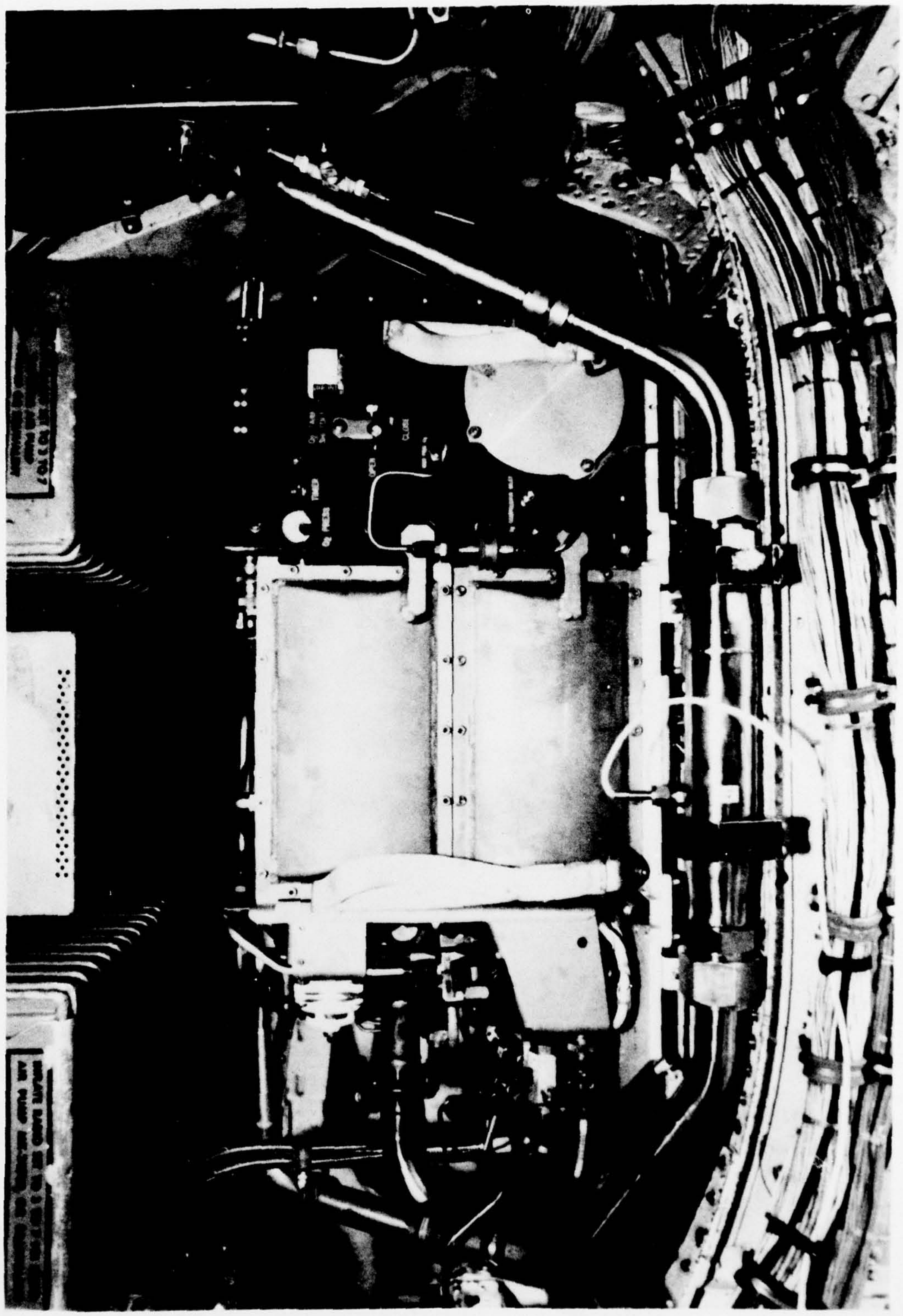

FIGURE 6 - Fluomine System Installed in the EA-6B.

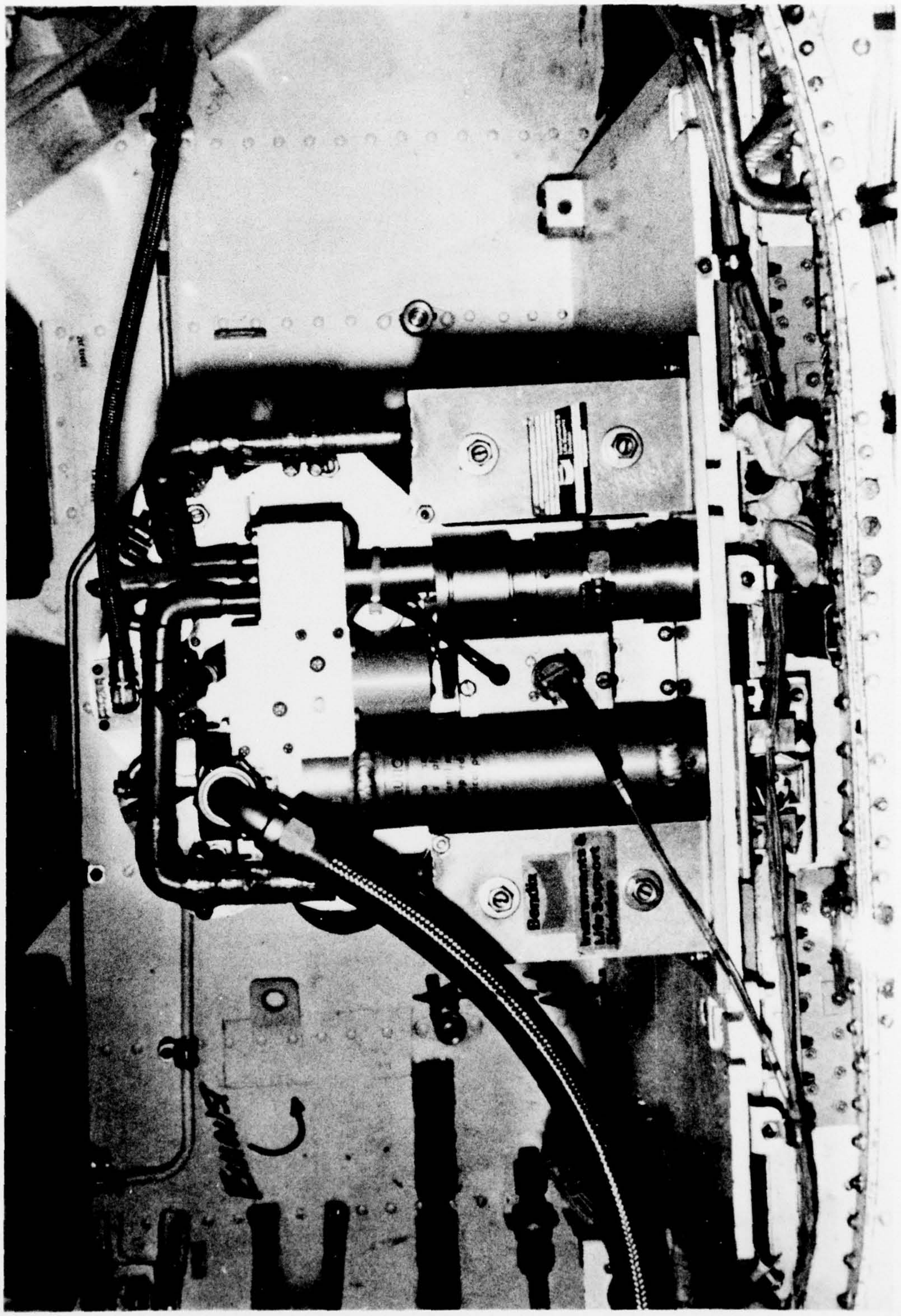

FIGURE 7 - Molecular Sieve System Installed in the EA-6B.

flight profile when it was drawn. Ground test behind an operating aircraft and launch/recovery operation remain. At the completion of the test of the molecular sieve system, the fluomine system will be installed in the aircraft and the flight test continued.

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